Ground Water Monitoring&Remediation

Cost-Optimal Contaminant Plume Management with a Combination of Pump-and-Treat and Physical Barrier Systems

by Peter Bayer, Michael Finkel, and Georg Teutsch

Abstract

The economic potential of combining hydraulic barriers and pump-and-treat systems to manage contaminant plumes is investigated by means of a comparative cost analysis. The analysis is based on a preceding study on the hydraulic performance of barrier-supported and conventional pump-and-treat systems, which revealed the efficiency of accurately positioned barriers in reducing pumping rates for contaminant plume capture. In the present paper, we examine whether the application of physical barriers like slurry walls or sheet piles also leads to economic benefits, i.e., whether the reduction of the operational costs outweighs the capital costs associated with the construction of the barriers. An economic model is presented that quantifies remediation costs by the use of cost functions relating costs to site-specific and system-specific parameters. The model is applied to a hypothetical remediation scenario. The results clearly demonstrate that physical barriers may yield significant savings in the total costs, particularly if unit costs for on-site treatment are high. Furthermore, as barriers tend to reduce the uncertainty about the pumping rate required to capture a plume, they smooth the trade-off curves between total remediation costs and system reliability.

Introduction

Operating pumping wells is likely to be the approach most often applied for controlling aquifer contamination, usually in combination with an on-site treatment facility where recovered contaminated water is cleaned up before it is discharged into surface water or local sewers or drained back into the aquifer. However, the pump-and-treat technology has revealed to be inadequate to achieve short-term remediation of the subsurface in many cases. Pumping alone is meanwhile regarded not suited to efficiently extract organic contaminations from the aquifer, where nonaqueous phases act as long-term sources, which permanently load the passing ground water with concentrations that stay nearly constant over huge time frames (Mackay and Cherry 1989; Haley et al. 1991; Berglund and Cvetkovic 1995; Grathwohl 2000).

Though a broad range of innovative remediation technologies or amendments to increase contaminant extraction rates have been proposed, at several sites, the prevailing conditions do not allow for methods alternative to pump and treat (Hoffman 1993; U.S. NRC 1997). Especially, hydraulic and/or hydrogeochemical site characteristics may narrow the number of applicable technologies. Innovative approaches such as enhanced bioremediation or cosolvent-supported methods represent not just ambitious but also sensible technologies, which have to be accurately adapted to a site. Uncertainties about the structure and the properties of the subsurface may represent a considerable risk for dispersing the reagents and, consequently, for the overall success (Massmann and Freeze 1987; Andersson and Destouni 2001; Teutsch et al. 2001). Therefore, hydraulic containment focusing on ground water protection rather than on its cleanup is still an important means in ground water management, though technologies designed for contaminant removal should be preferred if feasible.

We focus on improvement of conventional pump-and-treat systems (CPT), which are still appealing due to their flexibility, unspecific applicability, and the ability to fairly definitely measure hydraulic containment. However, in view of its inefficiency to reduce contaminant mass in the aquifer, CPT means long-term hydraulic containment rather than remediation. Experience so far indicates operation time frames of decades, which might even expand to hundreds of years (e.g., Voudrias 2001). The continuous expenditures for pumping, maintenance, and treatment are therefore crucial to the economic feasibility of pump-and-treat systems. Moreover, the uncertainty about the net present value of these operational costs represents a considerable additional economic risk factor.

The pumping rate is a major determinant in achieving adequate ground water capture (Boice 2002) and a dominating factor on the operational costs. Therefore, any measure that enables a reduction in the pumping rate required to establish hydraulic containment of a given contaminated area or contaminant plume is of general interest. In a preceding modeling study (Bayer et al. 2004), we proposed the employment of physical barriers along the edges of the contaminated source area to improve CPT. Comparison of these so-called barrier-supported pump-and-treat systems (BPT) with CPT revealed that additional physical barriers may have a tremendous impact on the performance of hydraulic containment by pumping wells. In the aforementioned study, we systematically examined the effect of a large spectrum of barrier settings on the pumping rate required for containment, but so far an economic assessment is missing. Though the implementation of additional barriers seems to bear a potential to reduce the operational costs, the initial costs of the BPT are higher than for CPT since additional expenditures arise for the installation of the barriers. BPT can only represent an attractive alternative to the conventional approach if the barrier costs can be compensated by a reduction in operational costs. This aspect is the central focus of the present study. It is discussed by means of a hypothetical site scenario where ground water is assumed to be treated by a sorptive removal system with granular activated carbon (GAC) as it is a standard practice at many sites contaminated with hydrophobic organic compounds.

Hydraulic Performance Characteristics of BPT and CPT Scenarios

Since the hydraulic performance investigation of BPT (Bayer et al. 2004) embodies the basis for the subsequent economic analysis, the major results of this study shall be briefly summarized herein to provide the groundwork necessary to understand the economical assessment discussed subsequently.

The geometric configuration of the CPT and BPT scenarios that are considered here is depicted in Figure 1. The scenarios were modeled within a two-dimensional ground water flow domain, assuming confined conditions. Barrier settings are implemented systematically in order to examine the effect of shape, length, and location of the barriers. Four BPT scenarios and the corresponding CPT scenarios provide the framework for a large spectrum of barrier settings, the hydraulic performance of which has been evaluated in Bayer et al. (2004). The flow calculations have been performed with the simulation software MODFLOW (McDonald and Harbaugh 1988), using the horizontal flow barrier package of MODFLOW to implement the physical barriers. The respective combined pump-and-treat–physical barrier systems were then analyzed by repeatedly performing two steps. First, the effect of the remediation system on the ground water flow conditions is modeled. Second, a particle-tracking algorithm (MODPATH, Pollock 1994) is used to examine whether the current design guarantees complete capture of the contaminated area to be controlled. The general objective of BPT is to deviate the ground water flow to achieve a reduction in the pumping rate of one well positioned downgradient of the contaminated area. This well shall capture the contaminated area at a minimum pumping rate.

For each BPT scenario, different settings of the barrier length, b (L), and the distance of the pumping well to the contaminated area, x (L), were examined and compared to CPT in terms of the required pumping rate in order to deduce the system sensitivities to geometrical design factors. Pumping rate values are provided as dimensionless values by normalizing the calculated pumping rate, Q_z (L^3 T^{-1}), with the respective Darcy flow, Q_D (L^3 T^{-1}), through the contaminated area in the modeled scenario (representative transmissivity, T_{rep} (L^2 T^{-1}), regional hydraulic gradient, i (−), and width of the contaminated area, w (L)):

$$Q'_z = \frac{Q_z}{Q_D} = \frac{Q_z}{T_{rep} i w} \tag{1}$$

Index z refers to the particular aquifer realization considered.

In doing so, the results of Bayer et al. (2004) can be used to derive real values of pumping rate, $Q_{real,z}$ (L^3 T^{-1}), at a certain site by multiplication of the Darcy flow through the contaminated zone at the site, $Q_{D,real}$ (L^3 T^{-1}), with the corresponding dimensionless value Q'_z,

$$Q_{real,z}(x_{real}, w_{real}, b_{real}) = Q_{D,real} Q'_z\left(\frac{x}{w}, \frac{b}{w}\right) \tag{2}$$

provided that geometrical similarity of the modeled scenario and the representation of the real site are satisfied. Geometrical similarity is defined by the ratios

$$\frac{x_{real}}{w_{real}} = \frac{x}{w} \tag{3a}$$

$$\frac{b_{real}}{w_{real}} = \frac{b}{w} \tag{3b}$$

Figure 2 summarizes the results, assuming homogeneous flow conditions. It was revealed that downgradient barriers (scenario C) lead to lower pumping rates than upgradient barriers (scenario B). If the barrier length is longer than the width of the contaminated area, it is preferable to subdivide a given barrier length into two parts (scenario D) with a longer segment at the downgradient edge of the area to be captured. For a barrier length >2.5 times the contaminated area width, the optimal solution is scenario E: a barrier that is tracked downgradient along the sides of the contamination starting from the upgradient edge.

In the preceding study, we further examined the performance characteristics of BPT and CPT under heterogeneous flow conditions based on Monte Carlo analyses comprising 500 equally probable realizations of the spatial transmissivity distribution. The transmissivity patterns were generated stochastically by unconditioned sequential Gaussian simulation (Deutsch and Journel 1992), assuming a lognormally distributed transmissivity $Y = \ln \bar{T}(x)$, with fluctuations of zero mean and variance σ_Y^2. The spatial correlation of Y was defined by the integral scale I_Y. Each

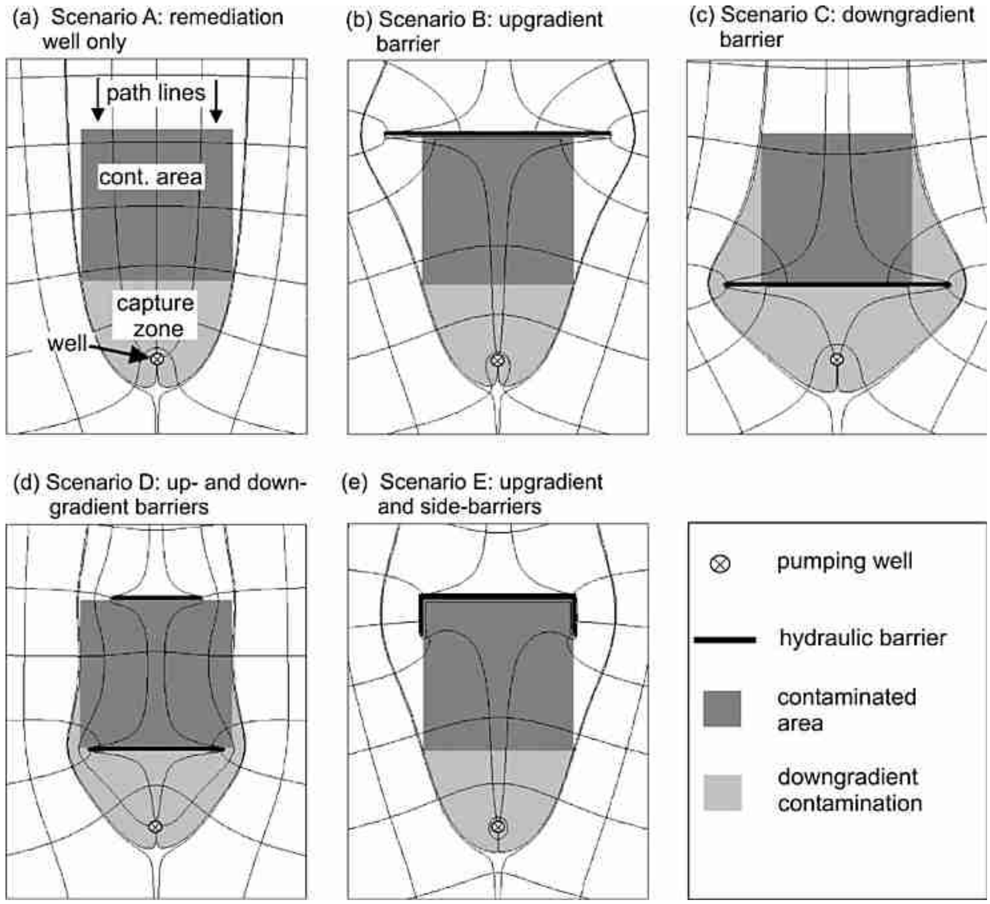

Figure 1. Scenarios with geometric arrangement of active and passive control systems (adopted from Bayer et al. 2004).

individual realization was subject to adaptation of the minimum pumping rate. For a given ensemble of 500 realizations, the calculated pumping rates were sorted to obtain probability density curves (pdfs) of the pumping rate. The analysis of BPT scenarios assuming heterogeneous aquifers was limited to certain settings with a given total barrier length: setting B* = scenario B with $b/w = 1$ (barrier along the complete upgradient boundary of the contaminated area), setting C* = scenario C with $b/w = 1$ (barrier along the downgradient boundary), setting D* = scenario D with $b/w = 2$ (one barrier along the upgradient boundary, one barrier along the downgradient boundary), and setting E* = scenario E with $b/w = 3$ (barrier along the upgradient boundary and the sides of the contaminated area). Furthermore, the distance between the well and the edge of the contaminated area was fixed to $x/w = 0.5$. Figure 3 illustrates the results for the two cases of aquifer heterogeneity addressed in the economic analysis subsequently. The results confirm the findings of the preliminary study for homogeneous conditions. Though the mean pumping rates increase with σ_Y^2 and I_Y, they generally are lower for BPT than for CPT. Aside from this, a main feature of the pdfs of the pumping rates calculated for BPT is the minor spreading, reflecting that barriers can reduce the sensitivity of pump-and-treat systems to variations in aquifer heterogeneity and, by this, raise the system robustness.

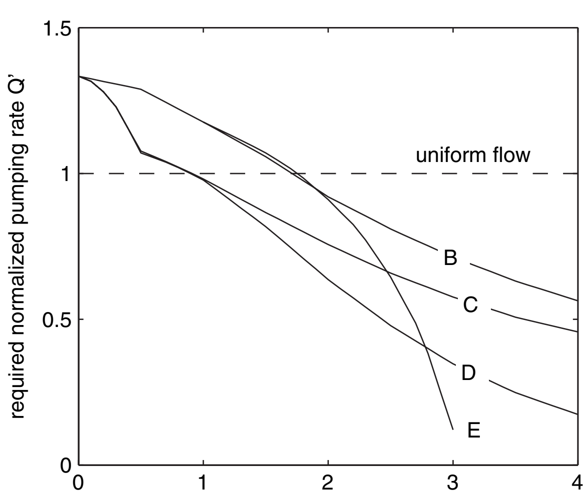

Figure 2. Relationship of Q′ and *b/w* for scenarios B to E for a given distance of the downgradient pumping well ($x/w = 0.5$) under homogeneous transmissivity distribution.

Framework for the Economic Analysis

Objective, Principles, and Assumptions

As the focus is set upon the economic comparison of BPT and CPT, we restrict the analysis to those costs that are directly related to the remediation systems: pumping and treatment costs, and for the BPT scenarios, additional

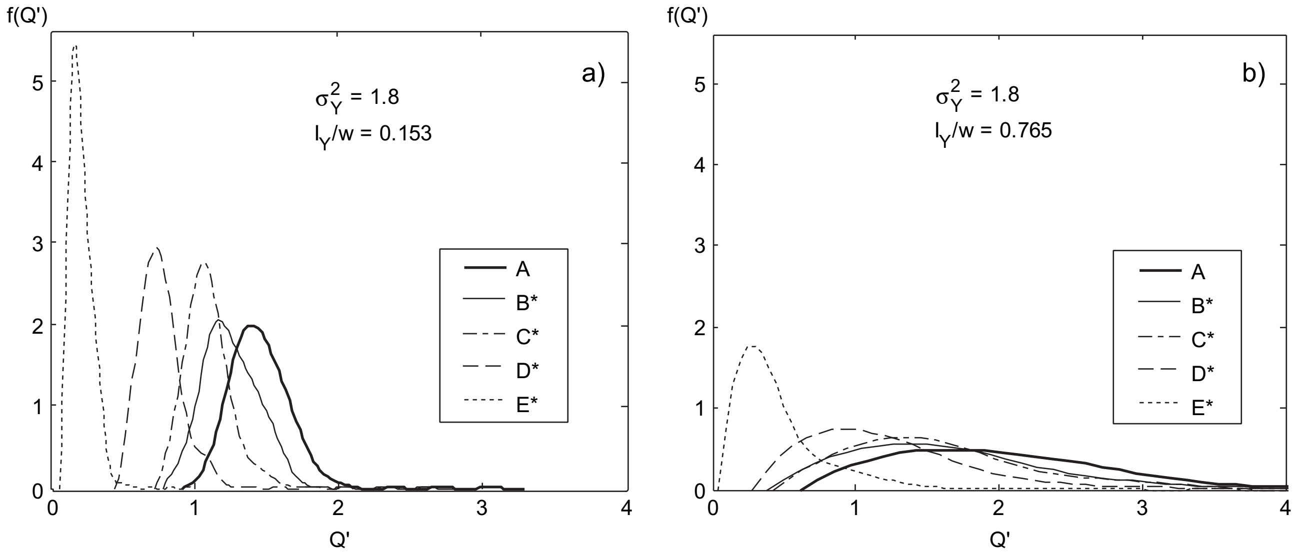

Figure 3. Probability density functions of Q′ for CPT scenario A (= A*) and settings B* to E* for an increasing integral scale I_Y of the spatial transmissivity distribution of the aquifer, as a result of the Monte Carlo analysis. The integral scale is generally expressed normalized to the width *w* of the contaminated area.

barrier installation costs. Expenditures for site investigation, site infrastructure, labor, and monitoring are assumed to be at a comparable level for CPT and BPT and are consequently not taken into account.

Operational and capital costs are commonly analyzed separately and finally summarized as total remediation costs. To relate these costs to technical parameters (e.g., pumping rate, dimension of the remediation system) by means of cost functions, it is necessary to break down the total costs into cost elements associated with single modules of work and technical equipment. Many of these cost elements, e.g., the purchase of GAC for the on-site water treatment facility, consist of both initial and operational payments. Furthermore, most of the treatment facility components do not endure over the entire operation time of the remediation measure, so reinvestments are necessary. These are also time-dependent costs and therefore operational costs (usually counted among capital costs). According to U.S. NRC (1997), all cost types are summarized and discounted to present valued total costs, TC (€):

$$\mathrm{TC} = \sum_{n=0}^{N} \frac{\mathrm{CE}_n (1 + r_\mathrm{p})^n}{(1 + r_\mathrm{i})^n} \quad (4)$$

where CE_n (€) is the cash expenditure of all cost elements in year *n* in which the costs incur. Parameter *N* represents the total number of years of expected expenditures, which usually equals the operation time of the remediation measure. Parameter r_p (−) denotes the inflation rate, and r_i (−) is the interest rate or discount rate. Please note that the inflation rate is assumed to be the same for each of the cost elements described subsequently. Different rates may apply to individual cost elements in reality but would unreasonably complicate the presented approach.

Decision Factors

Various factors have to be taken into account in deciding which remediation system to choose for solving a ground water contamination problem. Since the center of attention is the potential benefit from partial source containment, we try to limit our analysis to those factors that are considered to be most relevant to this particular problem. Five parameters are deemed to be major cost factors, i.e., are most relevant for the comparative cost calculation of CPT and BPT. The first cost factor is the geometry (size) of the site considered. With the assumption of a square area of contamination in our example, the size is expressed as the width of the contaminated area, w_real, which directly affects the pumping rate, Q_real (Bayer et al. 2004), and the barrier length, b_real. Similar to w_real, the natural ground water flow rate ($T_\mathrm{rep,real} i_\mathrm{real}$) also directly influences Q_real and is therefore a second parameter that is important to the economic comparison of CPT and BPT. A third cost factor is the concentration of contaminants in the pumped water. In the subsequent example, the contaminant concentration is assumed to be constant over time. Since CPT and BPT differ particularly with respect to the ratio between capital and operational costs, the expected operation time and the net interest rate for discounting future costs to net present values are two more parameters that will affect the decision on which technology concept to choose.

Cost Calculation

As aforementioned, total remediation costs are broken down into cost categories. Here, four different divisions are studied: (1) pumping costs; (2) GAC filling costs; (3) costs for the on-site treatment facility; and for BPT scenarios, (4) barrier construction costs. Continuous cost functions are obtained through mathematical regression based on site characteristics and real cost values. With these functions, unit price values that are staggered with the quantity purchased and efficiency increments (e.g., decreasing unit energy demand with increasing capacity of the pumping device) need to be considered. Though for an individual economic assessment step, functions might more properly reflect the site-specific conditions, continuous relationships generally facilitate analyzing the cost-driving parameters' relevance. A corresponding sensitivity analysis serves as a basic tool to identify cost-relevant factors and to quantify their influence on the predicted cost estimates. Furthermore, continuous cost functions are particularly suited to be used within an optimization framework since many optimization techniques work exclusively for steady functions.

Pumping Costs

In the present study, we limit the cost analysis for ground water extraction to the operational costs, which are mainly electricity costs. The pumping unit and further well equipment are covered by the cost function for the on-site treatment facility (see subsequently). Since the pump-and-treat scenarios examined here do not differ with respect to the number and the size of the wells, investment for the well installation is not included. One should note that the well installation costs are expected to be insignificantly low in comparison to other cost elements.

Even if the electricity costs constitute only a minor part of the total remediation costs, we present the derivation of the associated cost function in detail. This can be used as an example of the description of other cost elements, where similar cost functions are used. It is demonstrated that the nonlinearity of a cost function may result from staggered unit costs and/or from a rise in technical efficiency with an increasing number of units processed. Therefore, the same type of cost functions as shown in the following section (Equation 7) can be applied to estimate the costs of any other material consumption or operation of technical devices.

The electricity costs depend on the pumping rate, Q_{real}, and the duration of the measure (operation time). In addition, the electricity cost function comprises the effect that the efficiency and the energy demand of the pumping devices vary with the pumping rate. Typically, the efficiency factor of a pumping plant rises with capacity, so that the energy demand per unit water volume extracted declines with increasing pumping rate. This is expressed by an exponential regression with an exponent α that determines the efficiency increment

$$E_{\mathrm{T}} = dh\, aQ_{\mathrm{real}}{}^{\alpha} \tag{5}$$

where E_{T} is the energy demand per year (kWh/year or M L^2 T^{-3}), dh is the total dynamic head (lift and pressure loss, L), a (M $L^{1-3\alpha}$ $T^{\alpha-3}$) is a scaling factor, and Q_{real} (L^3 T^{-1}) is the pumping rate. Parameter α takes on values between 0 and 1. Equation 5 roughly approximates the energy demand. In practice, different pumps are selected at different flow rates and dynamic heads, with each of these pumps having an individual pumping efficiency function.

Usually, the unit price for electricity, P_{E} (€/kWh), is staggered by the supplier, i.e., a price discount is given with increasing consumption. This is also approximated by an exponential regression:

$$P_{\mathrm{E}} = lE_{\mathrm{T}}^{\lambda} \tag{6}$$

with a scaling factor l (€/kWh$^{1+\lambda}$year$^{\lambda}$) and an "attenuation" exponent λ that characterizes the price discount ($-1 < \lambda < 0$, typically $|l|<|a|$). Finally, multiplication of E_{T} and P_{E} leads to the annual electricity costs (see Figure 4 for an illustration):

$$C_{\mathrm{E}} = P_{\mathrm{E}}E_{\mathrm{T}} = lE_{\mathrm{T}}^{1+\lambda} \tag{7}$$

The annual pumping costs C_{E} constitute one element of the total cash expenditure, CE, and are discounted to a net present value (Equation 1). C_{E} is a function of Q_{real} as can be shown by inserting Equation 5 into Equation 7.

GAC Filling Costs

The sorptive removal by the use of GAC is applicable for the remediation of most organic contaminants. We assume direct treatment of the extracted ground water by GAC as a standard technology. Alternative options or extensions are treatment trains such as air stripping towers with subsequent GAC off-gas treatment, carbonate, or metal removal devices. However, these are not considered because cost calculation and comparison of different treatment systems are beyond the scope of this paper. Therefore, the calculations for GAC have to be seen as rough estimations that may differ for each site according to the particular technologies.

To calculate the costs for GAC, two issues have to be addressed concurrently: the volume of the GAC filling and the length of the exchange period. We assume that the contact time within the treatment unit is sufficiently long, i.e., kinetic sorption limitations can be neglected. The equilibrium loading of the GAC, which depends on both the GAC and the contaminant type as well as on the concentration of the contaminant in the extracted ground water, is described by a nonlinear Freundlich isotherm:

$$\frac{M_{\mathrm{S}}}{M_{\mathrm{GAC}}} = K_{\mathrm{F}}C_{\mathrm{W}}^{n_{\mathrm{F}}} \tag{8}$$

where K_{F} ($L^{3n_{\mathrm{F}}}M^{-n_{\mathrm{F}}}$)is the Freundlich coefficient, n_{F} is the Freundlich exponent, and C_{W} (M L^{-3}) is the contaminant concentration in water. Parameter M_{S} (M) denotes the mass of sorbed contaminant and M_{GAC} (M) the mass of GAC, whereas M_{S} is deduced from the contaminant load

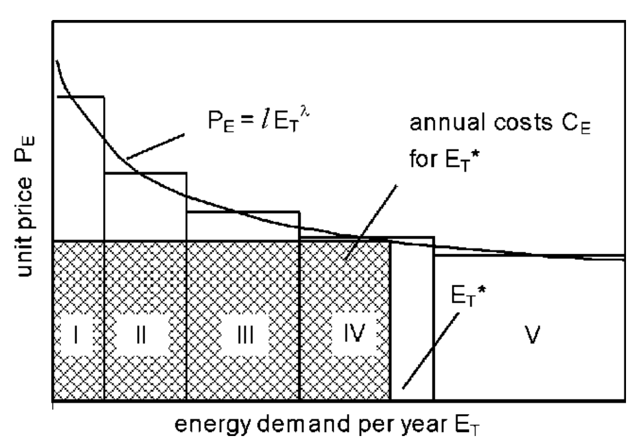

Figure 4. Calculation of unit energy prices, P_{E}, based on staggered/discounted prices (intervals of annual energy demand E_{T} *I − V*) by regression. The integral at a specific E_{T}^{*} gives the total annual energy costs.

F_C (M T^{-1}) in the extracted water and the length of the service life T_{GAC} (T) of the GAC filling until replacement:

$$M_S = T_{GAC} F_C = T_{GAC} Q_{real} C_W \quad (9)$$

The GAC demand per year, $M_{GAC,T}$ (M/year), is derived by combining Equations 8 and 9:

$$M_{GAC,T} = \frac{M_{GAC}}{T_{GAC}} = \frac{Q_{real}}{K_F} \cdot C_W^{1-n_F} \quad (10)$$

As for the pumping cost function, an exponential regression is used to describe staggered unit GAC prices, and annual expenditures for GAC are calculated using a formula similar to Equation 7:

$$C_{GAC} = g M_{GAC,T}^{1+\gamma} \quad (11)$$

where γ ($-1 < \gamma < 0$) is the regression exponent for GAC price discount, and g serves as a scaling factor (€/$M^{1+\gamma}$year$^{\gamma}$).

Please note that this calculation implies a complete loading of the GAC filling, which is not exactly accomplished in practice. However, assuming that a dual-bed system is used, the error is likely to only be marginal.

A matter of discussion is whether the concentration in the extracted ground water can be expected to stay constant over the long time frame that pump-and-treat systems are usually planned for. Observations typically show a temporal change, with concentrations decreasing over time. In many cases, however, a considerable decrease in contaminant concentrations is observed only in the very beginning of the measure. In the long term, concentrations usually remain at a fairly constant level over years. Therefore, the simplification of a constant contaminant concentration seems to be a reasonable assumption to answer "what ifs" of concentration levels for the economic comparison of CPT and BPT.

We further assume that concentration values do not differ between CPT and BPT. This is in contrast to the fact that any change of the flow regime may influence the contaminant release from residual source zones and thus contaminant concentration in ground water. However, this change is strongly dependent on the spatial distribution and composition of the source and can hardly be quantified in a reliable and general way.

Costs for the On-Site Treatment Facility

Design and equipment of the on-site treatment facility largely depend on the specific conditions prevailing at a contaminated site (e.g., ground water chemistry, infrastructure). For the scope of this study, we lump all components into a flat rate. Furthermore, the amount of expenditures is assumed to be a function of Q_{real}, the rate of extracted ground water. Since there is a given minimal value of contact time to be met, the size of the treatment facility evidently has to be adjusted to Q_{real}: the higher the Q_{real}, the higher the total costs for the facility, C_T. Mathematical regression is used to formulate the cost function:

$$C_T = f_1 + f_2 Q^{\rho} \quad (12)$$

where ρ is the regression exponent and f_2 (€ $L^{-3\rho}$ T^{ρ}) is a scaling factor. The constant, f_1 (€), represents the minimum cost to be paid for a small-size facility at low flow rates.

The on-site treatment facility has to be exchanged after a certain service life. Accordingly, the treatment facility costs accrue repeatedly. For instance, at a service life of 5 years, C_T is a cost element of total cash expenditures CE_0, CE_5, CE_{10}, and so forth (Equation 4).

Barrier Construction Costs

For the BPT scenarios, additional costs accrue for the construction of the hydraulic barrier (e.g., slurry walls or sheet piles). These costs, C_B (€), are calculated by

$$C_B = C_{B,SIC} + P_B m_b b_{real} \quad (13)$$

where $C_{B,SIC}$ (€) is the site installation costs, b_{real} (L) is the length of the barrier, and m_b (L) is its vertical extension. Parameter P_B (€/m^2) denotes the unit price for the barrier installation. It is assumed that barrier construction costs are not subject to maintenance. Please note that this may not be a valid assumption in the case of sheet piles and operation (planning) periods longer than 30 years (Enfield 2004).

Site Scenario and Assumptions

All pump-and-treat scenarios (Figure 1) are compared with respect to total remediation costs within the framework of an example site described subsequently for a planning period or operation time of 30 years. As described before, only those cost elements that differ between scenarios are covered by the economic model used in this study. Hence, the cost estimates given subsequently should be interpreted in terms of cost differences rather than by real total cost values, which are expected to be higher than the values presented.

Example Site

An example site is designed that is characterized by a square area of 100 × 100 m ($w_{real} = 100$ m) and contaminated by chlorinated hydrocarbons. Assuming that the contamination is dominated by *cis*-1,2-dichloroethylene (*cis*-DCE), remediation costs can be estimated by solely regarding *cis*-DCE. Furthermore, according to the assumptions of the hydraulic analysis, a confined aquifer (aquifer thickness $m_{real} = 15$ m) and uniform ground water flow is considered. The regional hydraulic gradient is set to $i_{real} = 0.0075$ and the mean hydraulic conductivity to $k_{real} = 0.001$ m/s. Given these characteristics of the example site, the rather high Darcy flow, Q_D, through the contaminated area, results in $Q_D = w_{real} k_{real} m_{real} i_{real} = 40.5$ m^3/h. The pumping well is located 50 m downgradient of the contamination. The concentration of *cis*-DCE in the pumped water is assumed to be $C_w = 500$ mg/m^3.

Cost Function Parameters

Besides the duration of the measure, the basic financial market indices such as the rate of interest r_i and the inflation rate r_p must be estimated to calculate total net present values of remediation costs (Equation 4). The respective parameters are set to $r_i = 7\%$ and $r_p = 3\%$.

The unit energy demand, a, of the pumping device (Equation 5) is set to 0.007 kWh/m^3/m, and the total dynamic head, dh, is assumed to be 10 m. The value of α is set to 1 since for simplification we assume that efficiency does not vary with the pumping rate. For the pumping plant, the unit electricity charge, P_E, is set to €0.08/kWh (Equation 6).

To calculate the amount of GAC needed (Equations 8 to 12), we use sorption isotherm values estimated from literature (Sontheimer et al. 1985): $K_F = 22.7$ mg/g (L/mg)^{n_F}, $n_F = 0.54$. The required contact time for the contaminant water and GAC is set to $T_{GAC} = 20$ min. For the GAC filling, the parameters are given by $g =$ €3.75/kg$^{1+\gamma}$year$^{\gamma}$ and $\gamma = -0.05$, thus resulting in an average unit price of €2.50/kg GAC.

The adjustment of the treatment facility cost function (Equation 12) to a series of real cost values provided by consultants (the original cost data are not free for publication) leads to the following regression parameters: $f_1 =$ €3000, $f_2 =$ €4000 (m^3/h)$^{-\rho}$, $\rho = 0.52$. A maintenance cycle of 10 years is assumed.

The hydraulic barriers within the BPT scenarios are slurry walls that are installed over the complete aquifer thickness, m (vertical extension $m_b = m$). Unit costs per area of wall differ depending on installation depth as well as stability and impermeability requirements. NFESC (2004) reports prices of €20/m^2 to more than €500/m^2. We assume that hydraulic barrier installation has to meet only moderate quality standards as possible leakages may reduce the local hydraulic blocking capability of a wall but will not seriously change the overall BPT performance. Hence, a comparatively low unit price of $P_B =$ €80/m^2 is charged for constructing the barrier, and site installation costs are estimated to be $C_{B,SIC} =$ €35,000 (Equation 13). However, it is evident that higher prices would favor CPT.

Economic Comparison of CPT and BPT

Comparison for Homogeneous Aquifer Conditions

For the first step, CPT and BPT are compared on the basis of the results of the hydraulic analysis for homogeneous aquifer conditions. The total costs of a CPT system are estimated to be €853,000, whereas expenditures for GAC filling amount to over 75% of the total costs (Figure 5). With regard to the BPT systems, the benefit of installing additional hydraulic barriers largely depends on the location and the length of the barriers. With a barrier that is located along the upgradient edge of the contaminated area (scenario B), it is not possible to reduce total costs regardless of the barrier length. For scenario E, which is equivalent to scenario B for $0 < b = 100$ m, a cost reduction appears only for a barrier length $b >$ ~220 m. For the other barrier locations examined (scenarios C and D), a benefit in terms of a reduction of total costs is obtained at almost any barrier length. The most preferable scenarios are scenarios C and E for $b = 100$ m, scenario D for 100 $m < b = 270$ m, and scenario E for 270 $m < b = 300$ m. The lowest cost scenario is scenario E with a barrier length of $b = 300$ m (equals setting E* used in the subsequent analysis for heterogeneous aquifer conditions). Total costs are reduced here to €498,000. The pumping rate is reduced from 54 m^3/h (CPT) to 10 m^3/h, and as a consequence, GAC filling costs are reduced to €86,000, which represent only 14% of the total costs.

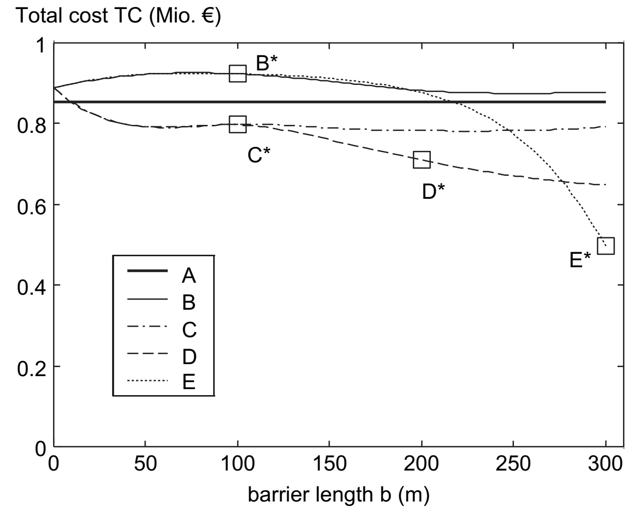

Figure 5. Total remediation costs for the example site for scenarios A to E, assuming a homogeneous aquifer. The settings B* to E* are processed for heterogeneous conditions.

After a first indication of the potential efficiency of a combined pump-and-treat–hydraulic barrier system, it is mandatory to know whether the application of BPT will lead to an economic benefit when major cost factors have values that are different from the aforementioned example. As already mentioned, there are numerous factors affecting the total remediation costs of CPT and BPT systems. However, of particular interest with regard to an economic comparison of CPT and BPT are those parameters that not only change costs in general but also have a distinct effect on the on-site treatment costs (Bayer et al. 2001, 2003). Since BPT's benefit compared to the CPT's can only be due to the lower pumping rate of BPT systems, we can generally state that the higher the specific on-site treatment costs (per unit volume of water to be treated), the higher the economic benefit for a BPT application in comparison to a CPT application. Consequently, every parameter that affects the unit treatment costs will possibly affect the ranking of CPT and BPT scenarios. In addition, the magnitude of discounting the annual cash expenditures for on-site treatment to net present values might be crucial: the lower the discount rate (interest rate), the higher the net present value of the treatment costs for the entire operation time of the remediation system. Therefore, a low discount rate and/or a high inflation rate will favor BPT compared to CPT. As a representative for all parameters that either affect the costs of the on-site treatment or their discount to net present values, we selected two parameters, C_W, the *cis*-DCE concentration in the extracted ground water, and r_i, the interest rate, to analyze their influence on total remediation costs of CPT and BPT. Figure 6 shows the cost savings obtained with BPT ($TC_{CPT} - TC_{BPT}$) in relation to the total costs of CPT for different values of C_W as a function of r_i. Parameter TC_{BPT} represents total costs of the economically best of all BPT scenarios. The lower limit of the r_i range is equivalent to no discount ($r_i = r_p = 3\%$). Starting with the parameter values assumed within the example site framework (relative savings ~42%), Figure 6 clarifies that even

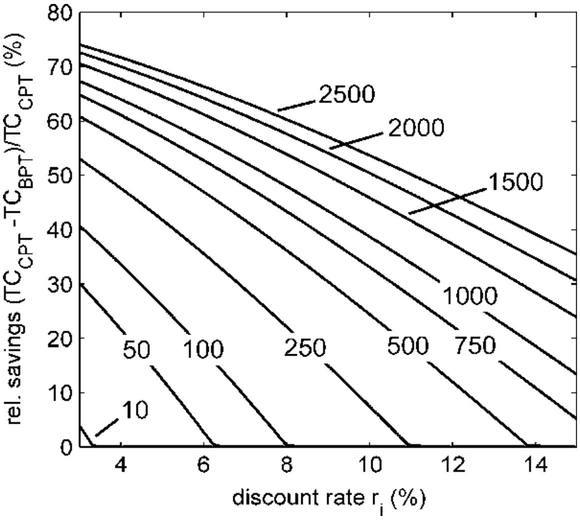

Figure 6. Total cost savings by barrier installation (best out of scenarios B to E) compared to CPT for variable discount rate and *cis*-DCE concentration C_W (10 to 2500 mg/m^3).

higher savings (up to >60%) are achieved if either a higher *cis*-DCE concentration or a lower interest rate is applied. The intersection of the curves with the x-axis reveals the limit where BPT becomes unfavorable. The respective discount rate constituting this limit declines with decreasing concentration C_W. At a *cis*-DCE concentration $C_W = 250$ mg/m^3, for example, CPT is preferred if r_i is above 11%.

To complete the parameter sensitivity analysis, Figure 7 shows the relative savings that may be obtained with BPT as a function of the natural Darcy flow, Q_D, for selected values of *cis*-DCE concentration, C_W. Two arrays of curves for different values of aquifer thickness m_{real} (15 m, as used previously, and 30 m) are shown. The discount rate is set to the default value $r_i = 7\%$. A characteristic feature of the curves of relative savings is a rather flat shape at the lower limit of the Q_D range followed by an

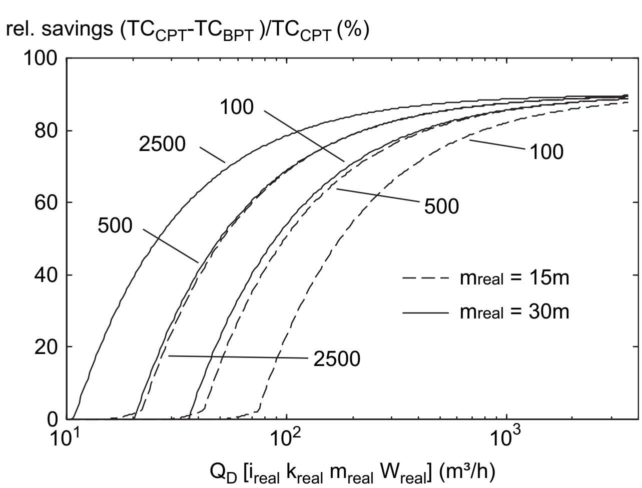

Figure 7. Total cost savings by barrier installation (best out of scenarios B to E) compared to CPT for variable Darcy flow, Q_D, and aquifer depth, *m* (equal to installation depth). Results are shown for *cis*-DCE concentrations C_W = 100, 500, and 2500 mg/m^3.

abrupt rise with a significant nonlinear hyperbolic shape, with increasingly higher cost savings at higher Q_D values. The change from a moderate to a steep slope stems from a change in the economically best BPT scenario (from scenario D to E). The sharp increase of the relative cost savings within a narrow range of Q_D values reflects a kind of switching point where the barrier construction costs are compensated by the lower treatment costs. The results support the general finding that higher treatment costs favor the application of BPT no matter whether this is caused by higher unit treatment costs or by a higher overall pumping rate due to a higher ground water flow rate (Figure 7). In addition, we can expect that BPT will be less attractive if the barrier construction costs are relatively high. Since they depend on the construction depth, the advantage of BPT over CPT is expected to be declining with increasing aquifer thickness. This is demonstrated in Figure 7 by an additional set of curves for an aquifer thickness $m_{real} = 30$ m. In comparison with the results for $m_{real} = 15$ m, all curves are shifted to the right. If we consider the aforementioned example site ($C_W = 500$ mg/m^3, $Q_D = 40.5$ m^3/h), the impact of the aquifer thickness becomes evident: assuming a constant value of Q_D, the relative cost savings using the BPT approach decrease from ~42% for $m_{real} = 15$ m to only 3% for $m_{real} = 30$ m (please recall our assumption: barrier construction depth m_b = aquifer thickness m_{real}).

Comparison for Heterogeneous Aquifer Conditions

To provide a sound basis for the economic assessment of BPT, it is advantageous to rate the "economic performance" of BPT with regard to cost estimates under uncertainty, i.e., if incomplete knowledge about aquifer transmissivity is taken into account by using a geostatistical description. Based on the hydraulic analysis (Bayer et al. 2004) providing Q_z' distributions for several ensembles of aquifer realizations, the economic analysis yields a total cost value, TC_z, for every single realization examined. Typically, some aquifer realizations represent conditions that are unfavorable to the performance of CPT or BPT. They consequently yield relatively high Q_z' and thus high TC_z, whereas relatively low costs result from those where the transmissivity distribution is beneficial to the efficacy of CPT or BPT. The highest value, max(TC_z), that is calculated for a given ensemble of 500 aquifer realizations is associated with the highest Q_z', max(Q_z'). As this maximum pumping rate guarantees complete capture for each of the 500 realizations, max(TC_z) can be expressed as the costs that have to be paid to have a system with maximum reliability (100%), with respect to the achievement of the expected goal: the complete capture of the contaminated area. In the same way, minimum costs, min(TC_z), are associated to min(Q_z') and therefore to a minimum system reliability (0.2% if total number of realizations = 500). By sorting all TC_z values in ascending order, a continuous elasticity curve is obtained, which relates total remediation costs to the performance reliability of CPT or BPT (Figure 8).

To focus on the influence of aquifer heterogeneity rather than geometric design parameters, the specific BPT settings B* to E* are compared with the CPT scenario A.

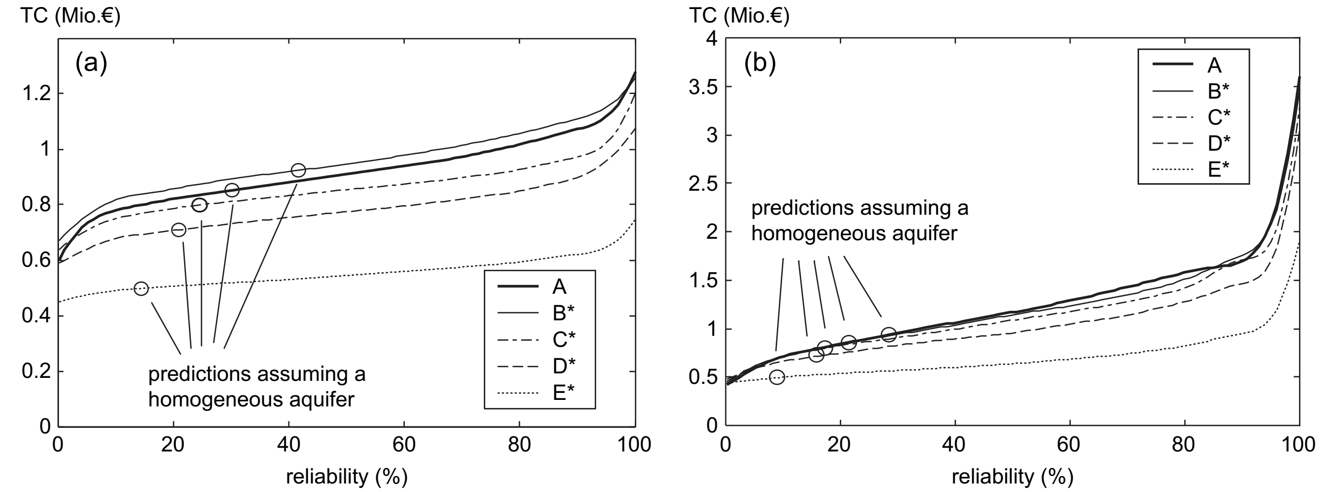

Figure 8. Cost-reliability trade-off for scenario A and BPT settings B* to E* at two heterogeneity levels (σ_Y^2 = 1.8; a: $I_{Y,\mathrm{real}}$ = 15.3 m, b: $I_{Y,\mathrm{real}}$ = 76.5 m) compared to the results from homogeneous aquifer (Figure 5).

Here, the barrier lengths are held constant for each setting, which is oriented at the corresponding scenarios. Settings B* and C* represent 100-m barriers along the complete up- and downgradient edge of the contaminated area, respectively. Setting D* is characterized by two barriers at both up- and downgradient edges. The total barrier length here is 200 m. For setting E*, the maximum barrier length for scenario E is considered (300 m).

Two ensembles of 500 realizations of the spatial transmissivity distribution are taken into account (cf. Figure 3). They possess the same variance ($\sigma_Y^2 = 1.8$) but differ with respect to the integral scale ($I_{Y,\mathrm{real}} = 15.3$ m for ensemble 1 and $I_{Y,\mathrm{real}} = 76.5$ m for ensemble 2). All other parameters are assumed to have the same values as described previously for the example site. As shown in Figure 8, all curves show a typical sigmoid form that results from the bell-shaped curves of the Q_z' distributions originating from the Monte Carlo analysis (Bayer et al. 2004). In accordance with the results of the hydraulic analysis showing an increasing Q_z' range with increasing integral scale, the range of TC_z values is noticeably larger for ensemble 2 (please note the different scales of the cost axis, Figures 8a and b).

Most significant is the sharp rise of the elasticity curves beyond a reliability of 90%. For ensemble 2, the remediation costs for 100% reliability are approximately twice as high as for a reliability of 90%. This is due to a small portion of transmissivity realizations apparently representing aquifer conditions that are adverse to the formation of an appropriate capture zone. These can be attributed to high-conductivity channels that direct the ground water flow away from the pumping well. The larger the integral scale, the larger the extension of these channels and consequently their negative impact on the required pumping rate and remediation costs.

The BPT setting E* proves to be by far the lowest cost option for both ensembles at any degree of reliability. Moreover, the BPT settings C* and D* yield lower costs than the CPT scenario A. The usefulness of an upgradient barrier (setting B*), however, appears to be particularly dependent on the degree of heterogeneity. While it is the worst option for ensemble 1, it is at least equivalent to CPT for ensemble 2. This might be an indication for a general advantage of the application of BPT that is obtained from blocking the aforementioned high-conductivity channels, which are particularly perceptible in highly heterogeneous aquifers.

Figure 8 also illustrates the inadequateness of design studies and cost predictions conducted under the assumption of homogeneous aquifer conditions ($\sigma_Y^2 = 0$). For all settings considered here, the pump-and-treat systems, which result from the analysis of homogeneous aquifer conditions, would achieve only poor performance reliabilities (depending on the setting between 10% and 40%) in heterogeneous aquifers, as represented here, by the two ensembles of aquifer realizations.

Summary and Conclusions

The use of barriers in addition to CPT has been shown to be a useful method to reduce the pumping rate required to hydraulically isolate contaminated aquifer zones. In the present study, we identified the relevant explanatory factors for a general economic comparison of CPT and BPT. Cost functions are formulated to relate and quantify the influence of site characteristics, technology design, and performance as well as economic factors on the expenditures for remediation system design.

The developed economic toolset has been applied to a hypothetical case of ground water contamination, which must be managed and controlled over the long term (30 years), by means of an appropriate pump-and-treat system downgradient of the contamination. Focusing on contamination control rather than on the extent of mass removal, the objective is to establish a complete capture of the plume and to treat the extracted water in a dual-bed system via sorptive removal onto activated carbon. CPT and BPT scenarios with different configurations of the hydraulic control elements are considered to find the cost-optimal system design.

For most of the BPT systems examined and for the greater part of the parameter spectrum analyzed, the economic benefit that arises from the pumping rate reduction is substantially larger than the additional costs that have to be paid for construction of the barriers. However, the economic benefit varies significantly depending on the location and the length of the barrier(s). High cost savings can be achieved when the barrier surrounds the contamination along the upgradient edge and at the sides (Figure 1, scenario E). In general, the savings increase with (1) increasing treatment costs per unit; (2) increasing amount of water to be treated; (3) decreasing net interest rate; and (4) decreasing construction costs per unit barrier length.

In addition, we have also analyzed CPT and BPT for heterogeneous aquifer conditions, assuming a random spatial transmissivity distribution. The results support the findings of the analysis for homogeneous aquifer conditions with regard to the ranking of BPT and CPT. Furthermore, elasticity curves are derived that delineate the relationship between remediation costs and system performance reliability. Since an additional physical barrier tends to reduce not only the mean pumping rate but also the spread of the pdf, the uncertainty about the remediation costs is reduced in two ways. First, the impact of the pumping rate on total remediation costs is diminished as the part of those costs that depend on the pumping rate are decreased. Second, the uncertainty about the remediation costs arising from the uncertainty of the appropriate pumping rate to achieve a complete capture of the plume is reduced.

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Biographical Sketches

Peter Bayer *is a researcher in groundwater management of the D-SITE working group at the Center for Applied Geoscience* *of the University of Tuebingen, Germany. He holds a Ph.D. in Hydrogeology, focusing on contaminant ground water modeling, system optimization, and environmental economics. He may be reached at the University of Tuebingen, Sigwartstr. 10, D-72076 Tuebingen; peter.bayer@uni-tuebingen.de.*

***Michael Finkel** completed his study in civil engineering at the University of Stuttgart, Germany, in 1990. Following the completion of his study he worked for several years as a consultant dealing with problems of ground water management and protection in the context of the planning of new high-speed railway lines in Germany. Since 1994 he has been employed at the Center for Applied Geology of the University of Tuebingen. In 1998 he gained his Ph.D. in the field of ground water flow and transport modeling. Since then he has been in charge of the D-SITE working group. He may be reached at the University of Tuebingen, Sigwartstr. 10, D-72076 Tuebingen; michael. finkel@uni-tuebingen.de.*

***Georg Teutsch** completed his study in geology and hydrogeology at the Universities of Tuebingen and Birmingham in 1980 with an M.Sc. in Hydrogeology. Following the completion of his studies, he worked for several years nationally and internationally as a hydrogeologist, concentrating on problems of water resources and water palnning. In 1988 he gained his Ph.D. in the field of ground water modeling in karst aquifers. Between 1986 and 1991 he led the ground water research group at the University of Stuttgart. In 1991 he gained his postdoctorate, thereafter becoming professor for Geohydrology at the University of Stuttgart. In 1993 he was appointed to the Chair of Applied Geology at the Geological Institute at the University of Tuebingen. Since 2004 he has been scientific director of the Umweltforschungszentrum (UFZ) in Leipzing, Germany. He may be reached at UFZ, Permoserstraße 15, D-04318 Leipzig, Germany; gf@ufz.de.*